

Compact Stellar Systems around NGC 1399

P. Firth^{*1}, M. J. Drinkwater¹, E.A. Evstigneeva¹, M. D. Gregg², A. Karick²,
J. B. Jones³ and S. Phillipps⁴

¹ *Department of Physics, University of Queensland, QLD 4072, Australia.*

² *Physics Dept, U.C. Davis, and IGPP, Lawrence Livermore National Laboratory, L-413, Livermore, CA 94550, USA.*

³ *Astronomy Unit, School of Mathematical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom.*

⁴ *Astrophysics Group, H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, United Kingdom.*

Accepted 2007 August 1, Received 2007 July 1

ABSTRACT

We have obtained spectroscopic redshifts of colour-selected point sources in four wide area VLT-FLAMES fields around the Fornax Cluster giant elliptical galaxy NGC 1399, identifying as cluster members 30 previously unknown faint ($-10.5 < M_{g'} < -8.8$) compact stellar systems (CSS), and improving redshift accuracy for 23 previously catalogued CSS.

By amalgamating our results with CSS from previous 2dF observations and excluding CSS dynamically associated with prominent (non-dwarf) galaxies surrounding NGC 1399, we have isolated 80 ‘unbound’ systems that are either part of NGC 1399’s globular cluster (GC) system or intracluster GCs. For these unbound systems, we find (i) they are mostly located off the main stellar locus in colour-colour space; (ii) their projected distribution about NGC 1399 is anisotropic, following the Fornax Cluster galaxy distribution, and there is weak evidence for group rotation about NGC 1399; (iii) their completeness-adjusted radial surface density profile has a slope similar to that of NGC 1399’s inner GC system; (iv) their mean heliocentric recessional velocity is between that of NGC 1399’s inner GCs and that of the surrounding dwarf galaxies, but their velocity dispersion is significantly lower; (v) bright CSS ($M_V < -11$) are slightly redder than the fainter systems, suggesting they have higher metallicity; (vi) CSS show no significant trend in $g' - i'$ colour index with radial distance from NGC 1399.

Key words: galaxies: kinematics and dynamics, galaxies: distances and redshifts, galaxies: star clusters, galaxies: clusters: individual: Fornax Cluster, galaxies: individual: NGC 1399

1 INTRODUCTION

The Λ CDM model of structure formation predicts many more satellite dark matter concentrations (sub-haloes) than are observed as light from their embedded baryonic matter – this is the well-known missing satellite problem (e.g. Kravtsov, Gnedin & Klypin 2004). Several explanations address this mismatch between theory and observation – for example that the Λ CDM model needs correction, that the dark matter dominated satellites are too faint to detect with present instruments, or that star formation was obstructed in the smaller dark matter concentrations during cosmic reionisation (Moore et al. 2006). Recent progress in this field has included the creation of increasingly high resolution computer simulations and the detection in our Lo-

cal Group of faint, dark matter dominated stellar systems (Belokurov et al. 2007).

Nearby galaxy clusters are physically and observationally appropriate environments to assess the frequency and distribution of compact stellar systems (CSS), the most luminous being potential sites of small-scale dark matter concentrations. These systems range in size from globular clusters (GCs: not considered to have dark matter) to dwarf galaxies (likely to have dark matter), and the intermediate-sized ultra-compact dwarf galaxies (UCDs: which may have dark matter). This paper reports a further step in our ongoing investigation of the distribution of CSS within the Fornax galaxy cluster.

The densely populated and highly evolved gravitational centres of galaxy clusters are ideal locations to study the interaction, merging and destruction of galaxies and subgalactic stellar systems. GCs and other CSS surround-

* E-mail: firth@physics.uq.edu.au

ing central cluster galaxies provide observable fossil evidence of cluster evolution (e.g. Moore et al. 1999). In nearby galaxy clusters, CSS are attractive observing targets as potential trace particles of galaxy assembly (e.g. Blakeslee 2000; Brodie & Strader 2006) – for example GCs, numerous around giant elliptical galaxies, are resistant (particularly the most massive examples) over long periods to disruption through tidal forces, and their metal abundance features confirm that they are as old as their host galaxies (Carretta et al. 2000). Being relatively bright point sources, CSS are excellent targets for wide-field photometry and multi-fibre spectroscopy.

Three major sub-populations of CSS are discussed in the literature.

- **Globular clusters (GCs)** are gravitationally bound to a specific host galaxy. These are normally found at $M_V > -11$ ($V \sim 20.4$ at the distance of the Fornax Cluster), and this magnitude marks a break in the metallicity and size distribution of Fornax CSS according to Mieske et al. (2006). Excluding the light-saturated innermost region, NGC 1399’s GC population has been progressively catalogued by several authors – Dirsch et al. (2004) published a spectroscopically-confirmed inner-GC system catalogue of 468 GCs (2 to 9 arcminutes from NGC 1399), and Schubert et al. (2004) added 160 GCs in the outer parts of the system (8 to 18 arcminutes from NGC 1399, although individual positions were not published). Due to incomplete wide-area redshift data for faint point source targets, the radial extent of NGC 1399’s GC system is uncertain – but it is estimated at 45 ± 5 arcminutes (220 to 275 kpc) from wide-area photometry (Bassino et al. 2006a).

- **Intracluster globular clusters (IGCs)** are a proposed population of GCs that are not gravitationally bound to a specific host galaxy, having either been tidally stripped from their host galaxy or formed *in situ* (West et al. 1995; Bekki et al. 2003b). West et al. (1995) proposed that this potentially large population of IGCs might account for the high GC specific frequency (S_N) of cluster core galaxies such as NGC 1399. IGCs are identified observationally by their location in intracluster space, outside the accepted radial and recessional velocity limits of galaxy-associated GC systems. Wide-area photometry by Bassino et al. (2003) suggested candidate IGCs up to 160 arcminutes from NGC 1399 which are not associated with other galaxies, and recently published wide-area spectroscopy (Bergond et al. 2007) has confirmed 61 isolated IGCs up to 34 arcminutes from NGC 1399. However, since cluster core giant elliptical galaxies have very extended GC populations and we lack information on their true spatial motion, it is practically impossible to conclusively determine whether specific GCs are really IGCs.

- **Ultra-compact dwarfs (UCDs)** are massive and relatively bright CSS with absolute magnitudes $-13 \leq M_V \leq -11$ and typical radii 3 to 5 times larger than GCs. Alternatively labelled ultra-compact objects or dwarf-globular transition objects (Mieske, Hilker & Infante 2002; Hasegan et al. 2005), they extend into the fundamental plane gap between GCs and dwarf galaxies. Three origins have been proposed for these systems – that they are the bright tail of the GC distribution (e.g. Hilker et al. 1999a; Drinkwater et al. 2000b; Phillipps et al. 2001; Mieske et al.

2002); or massive superstellar clusters formed in galaxy interactions (Fellhauer & Kroupa 2002; Marston et al. 2004); or the tidally-stripped remnants of early-type nucleated dwarf galaxies (Bekki, Couch & Drinkwater 2001; Bekki et al. 2003a). Following the detection of two unusually bright but compact objects by Hilker et al. (1999a), 60 spectroscopically-confirmed ‘UCDs’ (both bright and faint) have been catalogued in the central region of the Fornax Cluster (Drinkwater et al. 2000b, 2004; Gregg et al. 2007).

We will avoid the above descriptors, since they assume information about kinematics and origins which we do not possess. Instead we identify CSS sub-populations from an observational perspective as follows: (1) *bound CSS* are gravitationally bound to galaxies surrounding NGC 1399; the remaining CSS are either (2) *bright unbound CSS* with $M_V < -11$ (Mieske et al. 2006) or (3) *faint unbound CSS* with $M_V \geq -11$.

In this paper we describe 2004 November observations with the VLT-FLAMES multi-object spectrograph of the central region of the Fornax Cluster, and investigate the distribution of CSS around the giant elliptical galaxy NGC 1399. Our aims are twofold – to extend the redshift-confirmed catalogue of radially-dispersed CSS surrounding NGC 1399; and to investigate whether there are kinematically and photometrically distinct sub-populations (Mieske et al. 2006) of bright and faint CSS that are not gravitationally bound to other cluster galaxies.

In section 2 we describe our VLT-FLAMES observations and results. In section 3 we separate the CSS likely to be gravitationally bound to prominent galaxies surrounding NGC 1399. In section 4 we analyse the projected radial distribution, recessional velocity dispersion and photometric properties of the unbound CSS, and in section 5 we summarise our key findings.

Throughout this paper we assume a distance to NGC 1399 of 18.6 Mpc (Richtler et al. 2000) which corresponds to a distance modulus ($m - M$) $\simeq 31.35$.

2 VLT-FLAMES OBSERVATIONS

The region within a 1° (~ 350 kpc) radius of NGC 1399 contains numerous extended light sources (mostly elliptical and lenticular galaxies) and unresolved point sources. Photometric catalogues of this region (Ferguson 1989; Hilker et al. 1999a; Hilker et al. 1999b; Karick, Drinkwater & Gregg 2003) provide a good starting point to study the distribution of CSS, since the numerous GCs around NGC 1399 dominate the point source population (compared to foreground Galactic stars and background galaxies) and can be fairly reliably colour selected.

In order to unambiguously eliminate foreground stars and background galaxies and to locate individual cluster members, we have obtained spectroscopic redshifts of colour-selected point sources over a relatively large projected area (four 25-arcminute diameter fields surrounding NGC 1399). Fortunately, the Fornax Cluster is relatively isolated in redshift space – its recessional velocity boundaries are 600 to 2500 km s^{-1} (Phillipps et al. 2001; Gregg et al. 2007). Our results add to those from the original compact object redshift surveys by Hilker et al. (1999a)

and Drinkwater et al. (2000a), and subsequent deeper redshift surveys (Dirsch et al. 2004; Drinkwater et al. 2004; Schubert et al. 2004; Bergond et al. 2007; Gregg et al. 2007).

We previously surveyed the region around NGC 1399 for CSS with the Two-degree Field multi-object spectrograph (2dF) on the Anglo-Australian Telescope (AAT) down to $b_J \sim 19.8$ (Drinkwater et al. 2000b), and the work of Gregg et al. (2007) extends this to $b_J \sim 21.5$. Our VLT-FLAMES observations were designed to access fainter targets ($r' < 22.75$ or approximately $b_J < 23.25$) with higher-resolution spectroscopy. Although we did not achieve signal-to-noise levels sufficient to study internal stellar populations, we have extended the faint end of the wide-area CSS distribution in the Fornax Cluster and significantly improved recessional velocity accuracy for 22 known CSS found with 2dF.

We observed 110-120 targets in each of four 25-arcminute diameter fields (NE, SE, NW and SW) surrounding NGC 1399 – the field coordinates, exposure times and target details are summarised in Table 1.

2.1 Target selection

Our targets were selected from a SExtractor-derived (Bertin & Arnouts 1996)¹ catalogue obtained through deep imaging of the Fornax Cluster with the CTIO Mosaic Imager at the 4-m Blanco Telescope in Chile (Karick 2005). These images, covering an approximately $70' \times 70'$ region centred on NGC 1399, are in the SDSS five-colour ($u'g'r'i'z'$) wide-band photometric system. They have limiting magnitudes of $g' \sim 25.1$ and $r' \sim 24.3$, and a seeing-limited resolution between 0.8 and 1.24 arcsec (~ 70 – 110 pc at the Fornax Cluster distance). We selected point source targets based on their similarity to a point-spread function (i.e. having an r' -band stellarity index ≥ 0.7).

Subsequent to our observations, we obtained dereddened $g'r'i'$ photometry (Karick, Drinkwater & Gregg 2007), calibrated to SDSS DR4 using the extended Landolt stellar library (Stetson 2000). We use this photometry through the rest of our paper. The average colour offsets between the original and revised photometry for our targets across the four VLT fields are $g' - r' \simeq -0.17$ mag and $r' - i' \simeq +0.06$ mag.

Fig. 1 shows the distribution of point source targets in colour-colour space. CSS in the Fornax Cluster are generally found within or close to the well-defined locus of Galactic stars from lower-left to upper right, reflecting the dominant F-G-K main sequence spectral types of their stellar populations. We selected ~ 2100 point source targets within a region of colour-colour space encompassing the known 2dF-derived CSS in Fornax ($0.37 < g' - r' < 1.07$ and $-0.06 < r' - i' < 0.64$ in the revised photometry). To compare our redshift results we specifically included several of the 2dF-derived CSS located within our field boundaries, and we prioritised the remaining targets by r' magnitude.

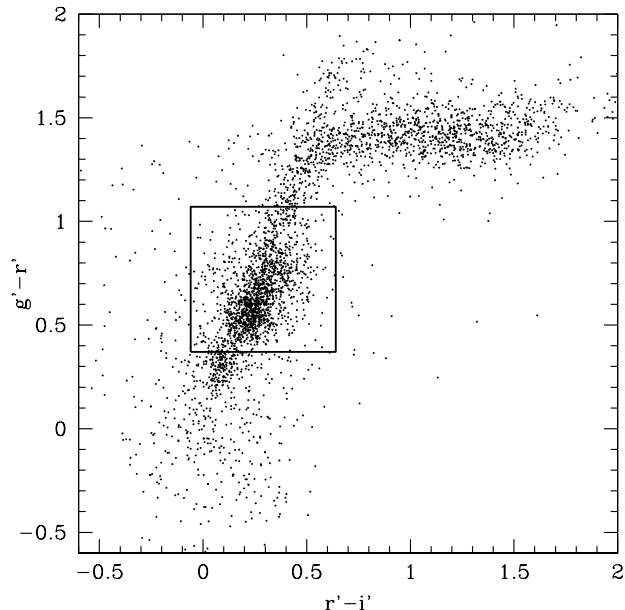


Figure 1. Colour-colour plot ($r' \leq 22.75$) of Fornax Cluster potential point source targets within the VLT-FLAMES field boundaries. Our VLT-FLAMES target selection box avoids the numerous red Galactic stars in a horizontal band at upper right.

2.2 Observations

Our observations over two nights in 2004 November at Cerro Paranal, Chile were made under ESO observing programme 074.A-0508 with the FLAMES multi-fibre intermediate to high-resolution spectroscopic system attached to the Nasmyth-A focus of the 8-m Kueyen telescope. Each fibre has an aperture of 1.2 arcsec, requiring accurate target astrometry for reliable results – since seeing during the observations was generally less than this aperture, the signal obtained was optimal (see Table 1).

With no automatic dispersion correction (ADC), the VLT can efficiently observe only relatively narrow wavebands. We selected bands LR2 (λ 3964–4567Å, R 6400) and LR4 (λ 5015–5831Å, R 6000) covering several strong absorption lines, including the Balmer series (H β 4861Å, H γ 4340Å, H δ 4102Å), CaII H and K (3968Å and 3934Å), the CH molecule or G band (4324Å), the Mgb triplet (5167–5184Å) and a number of FeI lines. We used the intermediate-resolution spectroscopy mode (600 lines mm⁻¹ and a blaze angle of 34°) in order to maximise the number of targets observed at a S/N level sufficient to identify these key absorption lines. Resolution elements in the raw image are 0.094Å (LR2 filter) and 0.136Å (LR4 filter), but after sky subtraction and other pipeline processing this increases to 0.2Å per bin. At this resolution a single absorption line feature can achieve a recessional velocity error of $cz \sim 15$ km s⁻¹, but combining multiple features further reduces this error to a few kilometres per second.

2.3 Data reduction and redshift measurement

Raw spectral images were processed using the default settings with VLT-GIRAFFE pipeline data reduction soft-

¹ The Source Extractor software package is available from <https://sourceforge.net/projects/sextractor>.

Table 1. VLT-FLAMES Observations

Field Name	RA (J2000) <i>h:m:s</i>	Dec (J2000) <i>d:m:s</i>	Targets	Faint Limit		Blue 3964–4567Å		Red 5015–5831Å	
				<i>g'</i> -band <i>mag</i>	<i>r'</i> -band <i>mag</i>	Seeing <i>arcsec</i>	Exposure <i>min</i>	Seeing <i>arcsec</i>	Exposure <i>min</i>
NE	03:39:40	-35:12:00	114	23.6	22.5	0.5–0.8	100	0.9–1.9	100
SE	03:39:30	-35:36:45	119	23.5	22.3	0.5–0.9	103	1.4–3.1	115
NW	03:37:17	-35:15:27	118	23.1	22.4	0.5–0.9	105	0.7–1.0	105
SW	03:37:15	-35:38:30	117	23.4	22.4	0.6–1.2	120	0.5–0.7	120

ware². Sky-subtracted spectra were then examined with IRAF’s SPLOT task to eliminate remaining sky features, cosmic rays, and CCD light leakage. To obtain redshifts we used IRAF’s XCSAO to initially cross-correlate (Tonry & Davis 1979) target spectra in each wavelength band to 1.4Å-resolution standard stellar templates (Jacoby, Hunter & Christian 1984), identifying the VLT-FLAMES target spectra with the highest cross-correlation R -values. We then used these target spectra as cross-correlation templates, having the required resolution (0.2Å) for higher precision cross-correlation to the remaining VLT-FLAMES target spectra.

We identified acceptable redshift measurements through cross-correlation R -values as follows

- In general, we selected the redshift result of the template with the highest R -value in either the blue or red waveband, using as a reliability threshold the minimum R -value of 4.2 for the 22 Fornax Cluster CSS originally discovered with 2dF and reconfirmed in our VLT-FLAMES results.
- We rejected as unreliable cross-correlation results for targets where the highest R -value was less than 3.
- Multiple independent wavelength bands are preferable to confirm the redshift of targets for which we only have low S/N, narrow waveband spectra. For targets with highest R -values between 3 and 4.2, we accepted those that produce similar redshifts for a majority of templates in both independent VLT-FLAMES wavebands (obtained on different nights). For the remainder, we individually inspected and assessed the strength of their absorption features in the blue and red wavebands.

2.4 Results

Fig. 2 summarises our results by apparent magnitude – we observed 468 targets from our colour-selected point source catalogue, and finally accepted 156 redshifts (from 289 redshifts with R -values ≥ 3). The accepted redshifts comprise 98 Galactic stars ($cz < 600 \text{ km s}^{-1}$), one background galaxy and 57 Fornax Cluster objects ($600 \leq cz \leq 2500 \text{ km s}^{-1}$). Of 133 targets whose redshifts we rejected from individual inspection of their spectra, only 7 had (poorly correlated) redshifts within the Fornax Cluster range.

The 57 confirmed Fornax Cluster objects comprise 4 known member galaxies (cross-checked with NED³ and in-

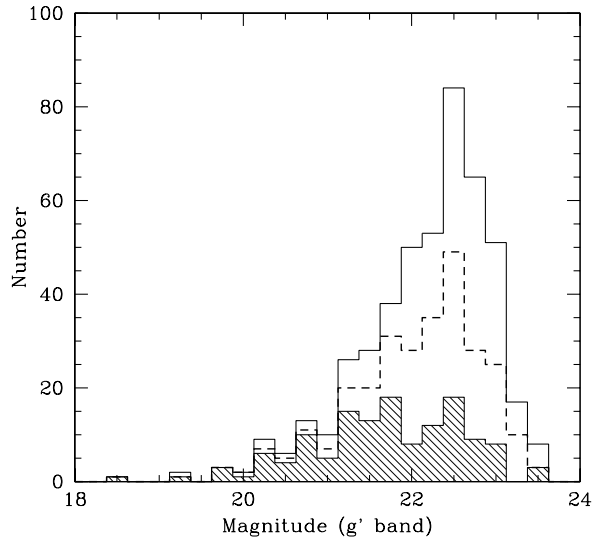


Figure 2. Redshift measurement success of our VLT-FLAMES observations within the g' -band range of our target catalogue. The upper line shows 468 observed targets in the four VLT-FLAMES fields. 289 measured redshifts with an R -value ≥ 3 are shown by the dashed line, and 156 finally accepted redshifts are represented by the hatched region.

advertently targeted due to point source confusion by SExtractor), and 23 known and 30 new CSS. As Fig. 3 shows, we have significantly extended the faint limit of known redshifts in our target catalogue.

Table 2 lists positions, photometry and recessional velocities for the cluster dwarf galaxies and CSS observed in our four VLT-FLAMES fields, together with 2dF-derived CSS which are potentially bound to prominent galaxies surrounding NGC 1399 (see analysis in the next section). Fig. 4 compares our VLT-FLAMES recessional velocity measurements with 2dF results by Drinkwater et al. (2000b) and Gregg et al. (2007). The results are comparable (the VLT-FLAMES velocity mean for 22 re-observed CSS is 19.5 km s^{-1} lower than the 2dF velocity mean) except for the CSS at RA 03:37:43.49, Dec -35:15:10.2 (identified as UCD-22), for which however a Mieske et al. (2004) measurement confirms our result. Our observations have reduced the average 2dF velocity error margin (73 km s^{-1}) to only 6 km s^{-1} .

² <http://www.eso.org/projects/dfs/dfs-shared/web/vlt/vlt-instrument-pipelines.html>

³ The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Tech-

nology, under contract with the National Aeronautics and Space Administration (<http://nedwww.ipac.caltech.edu>).

Table 2. Bound and Unbound CSS. Coordinates (J2000) and de-redenned photometry are from recalibrated CTIO imaging (Karick et al. 2007). The stellarity index (sgc-r), derived by SExtractor from r' band photometry (Karick 2005; Karick et al. 2007), compares the target light profile to a point-spread function (0 extended object; 1 point source). Velocities (cz) are heliocentric recessional. 2dF revised velocity data are derived from Drinkwater et al. (2000b) and Gregg et al. (2007). FCOS data are from the Fornax Compact Object Survey (Mieske et al. 2004). Bergond data are from VLT-FLAMES spectroscopy (Bergond et al. 2006). R -values shown in brackets are from the previously published redshift measurement with the lowest error margin. The full version of this table can be found in the Supplementary Material section of the online paper at <http://www.blackwell-synergy.com>.

R.A.	Dec.	g'	r'	i'	sgc-r	2dF	FCOS ^b	Bergond	VLT-FLAMES		Allocation	
$h\ m\ s$	$d\ m\ s$	mag	mag	mag		$km\ s^{-1}$	$km\ s^{-1}$	$km\ s^{-1}$	$km\ s^{-1}$	R -value.	Galaxy	$[\Delta v]/v_{esc}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
Known Fornax Cluster dE Galaxies												
03 36 37.25	-35 23 09.4	20.87	20.34	20.12	0.38				1401±13	3.6	FCC 171	
03 37 17.91	-35 41 57.6	20.55	19.93	19.65	0.00	1237±84			1279±13	3.7	FCC 194	
03 39 13.30	-35 22 17.2	19.20	18.54	18.20	0.03		824±24		794±6	9.9	FCC 222	
03 40 23.54	-35 16 36.5	20.52	19.89	19.60	0.03	2045±107			1814±11	4.0	FCC 241	
Known Fornax Cluster CSS												
03 36 22.23	-35 36 34.4	20.29	19.77	19.51	0.98	1462±76			1282±10	5.7		
03 36 26.67	-35 22 01.5	20.20	19.42	19.11	0.05 ^c	1499±117			1315±8	6.6	NGC 1381	4.1
03 36 27.69	-35 14 14.0	20.12	19.27	18.90	0.95	1297±45		1386±4		(29.6)	NGC 1381	3.4
.
.
New Fornax Cluster CSS												
03 36 36.31	-35 21 58.6	22.04	21.44	21.13	0.98				1415±44	3.0		
03 36 51.67	-35 05 35.1	21.39	20.92	20.70	0.98				1869±20	3.2	NGC 1380	0.1 ^a
03 36 54.57	-35 39 26.9	21.39	20.79	20.52	0.98				1469±10	5.1		
.
.

a. These CSS are considered to be gravitationally bound to a prominent cluster galaxy other than NGC 1399 - see analysis in the text.

b. FCOS catalogue identifiers (as sequenced in the table): 1-017, 2-0231, 2-078, 4-2028, 2-073, 0-2025, 3-2027, 1-2053, 1-060, 3-2004, 1-2083 and 3-2019.

c. Photometry of these CSS has been affected by partial blending with adjacent stars.

d. UCD3 is known to have an extended stellar halo (De Propris et al. 2005), and may be eventually classified as a dE,N galaxy.

e. Photometry of this CSS has been affected by blending with a background galaxy.

2.5 Assessment of target selection criteria

Having identified a significant number of spectroscopically-confirmed Fornax Cluster CSS, we can now assess the effectiveness of our target selection criteria. Table 2 shows that nearly all the new, faint CSS are point sources with r' -band stellarity index ≥ 0.97 . CTIO images of the new systems confirm that they are unresolved point sources at 1 arcsec resolution, although as noted in Table 2 the stellarity index values of 4 CSS have been reduced by blending with adjacent non-cluster objects.

Fig. 5 compares the colour-space distribution of redshift confirmed CSS to the point source targets in our four VLT-FLAMES fields. A two-dimensional K-S test (Press et al. 1992) shows a statistically significant difference (K-S D -statistic 0.28, probability statistic⁴ < 0.001) between these two distributions – spectroscopically-confirmed CSS generally have higher $r' - i'$ at given $g' - r'$ than the stellar locus.

Our redshift results have implications for future targeting of CSS in the Fornax Cluster central region. Of 156 accepted redshifts in our data, 4 were known galaxies and 22 were known Fornax UCDs, leaving 130 previously unknown redshifts from which our new faint CSS (31 objects listed in Table 2) represent a yield of ~ 25 per cent. Based on our results, we could with hindsight have applied more restrictive target selection criteria to maximise our likelihood of finding the *fainter* Fornax CSS by

- (i) Further restricting our point source catalogue to those

having an r' -band stellarity index ≥ 0.97 . This would not apply to surveys for the more luminous CSS, which are sometimes more extended (with lower stellarity index values).

- (ii) Limiting our targets to those having $g' - r'$ colours between 0.45 and 0.9 (see Fig. 5).

- (iii) Additionally limiting our targets to those with colour index $(g' - r') \leq 2(r' - i') + 0.2$, placing them to the right of the line shown in Fig. 5 and excluding a significant number of targets located within the overall stellar locus (see Fig. 1).

Although we would have missed targeting a small number of the newly-discovered CSS, we estimate that these tighter selection criteria would have significantly increased our faint CSS yield to ~ 45 per cent of the accepted redshifts.

3 ELIMINATING CSS BOUND TO GALAXIES SURROUNDING NGC 1399

The accumulated catalogue of radially-dispersed, redshift-confirmed CSS (2dF plus VLT-FLAMES) extends 47 arcminutes radially from NGC 1399, encompassing many prominent (non-dwarf) cluster galaxies within the Fornax Cluster central region. To analyse the distribution of CSS potentially associated with NGC 1399, we firstly eliminate systems that are satellites of (i.e. gravitationally dominated by) these prominent galaxies. Our approach is to provisionally associate CSS with a cluster galaxy if they are located within (or not far outside) its projected tidal radius – de-

⁴ The probability statistic measures the likelihood that both samples are randomly selected from the same underlying population.

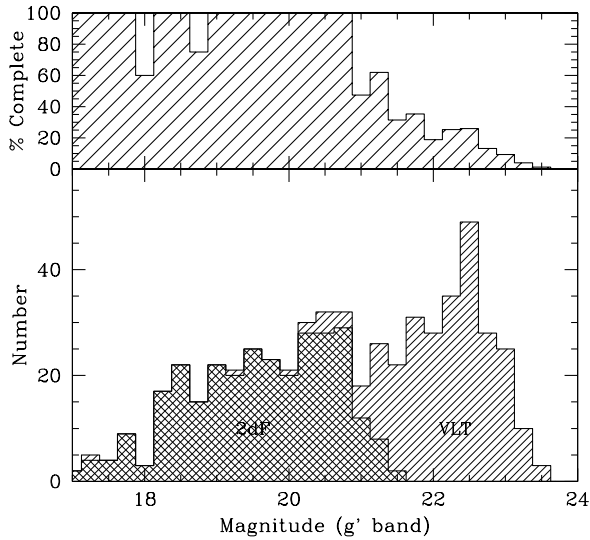


Figure 3. Combined 2dF and VLT-FLAMES redshift completeness for colour-selected point sources in the four VLT fields. UPPER: The redshift information is essentially complete to $g' \leq 20.7$, and we can make reasonable inferences about the unknown redshifts to a faint limit of $g' \sim 23$. LOWER: Redshift information from 2dF observations has been significantly extended by our VLT-FLAMES results.

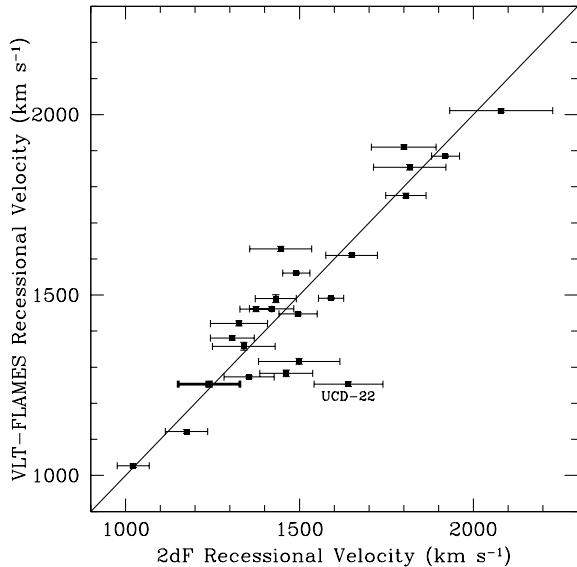


Figure 4. Comparison of VLT-FLAMES recessional velocities for 22 reconfirmed CSS with those published by Drinkwater et al. (2000b) and Gregg et al. (2007). 1σ VLT error bars are considerably smaller than the previous 2dF results. All 2dF data points are within $\sim 2\sigma$ of the equality line, except UCD-22 (RA 03:37:43.49, Dec -35:15:10.2) for which however Mieske et al. (2004) measured a recessional velocity (heavier error bar to the left) that is confirmed by our result.

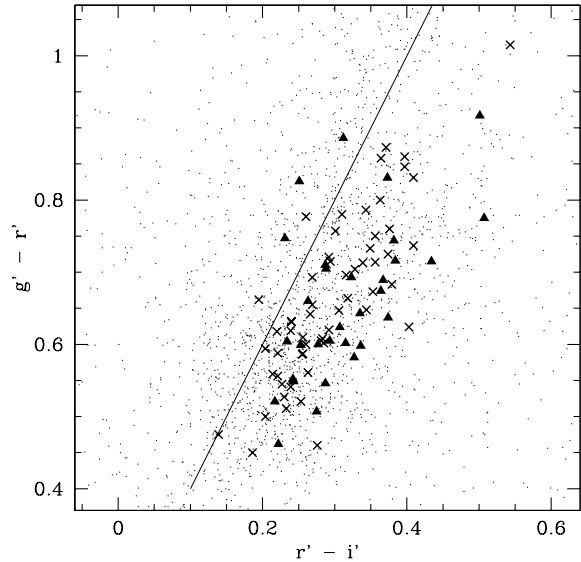


Figure 5. Colour-colour plot of point sources (dots) in our four VLT-FLAMES fields, compared with the distribution of spectroscopically-confirmed Fornax Cluster CSS from 2dF (crosses) and from our VLT observations (triangles). The sloping line represents a potential future target selection criterion (discussed in the text) that would maximise our CSS yield.

terminated by the opposing gravitational forces of the galaxy and NGC 1399.

Table 3 lists the coordinates and observed features of the prominent Fornax Cluster galaxies within 1° of NGC 1399, obtained from the Fornax Cluster Catalogue (Ferguson 1989) and from HyperLEDA⁵. Since HyperLEDA does not contain central velocity dispersion measurements for all these galaxies, we obtained a B_T to σ conversion relation ($\log(\sigma^4) = [16.0 \pm 0.8] - [0.6 \pm 0.7]B_T$ based on the Faber-Jackson relation, which depends upon the virial theorem) from 15 elliptical or lenticular galaxies having σ measurements, as shown in Fig. 6. We then applied this conversion to obtain the estimated σ values shown in italics in Table 3.

Nearly all of the galaxies are elliptical or lenticular, for which we have calculated virial masses (m_{vir}) from their effective radii (R_{eff} containing half the luminosity) and central stellar velocity dispersion (σ), using the formula $m_{vir} \simeq R_{eff}(1.65\sigma)^2/G$ (Padmanabhan et al. 2004). For the two spiral galaxies FCC 121 and FCC 285, we have calculated dynamical masses (m_{rot}) from HyperLEDA data, using the formula $m_{rot} = R_{25}V_{max}^2/G$. R_{25} is the radius along the projected major axis at the isophotal level 25 mag arcsec⁻² in the B-band, and V_{max} is the maximum rotation velocity corrected for inclination. To derive tidal radii we use the Jacobi limit approximation $r_t \simeq (m/3M)^{1/3}D$ (Binney & Tremaine 1987) where m is the mass of a prominent galaxy calculated as above, M is the mass of NGC 1399 estimated from X-ray emission (Jones et al. 1997), and D is the projected separation. As expected, the average tidal radius is smaller for galaxies closer to NGC 1399.

⁵ We acknowledge the usage of the HyperLEDA database (Paturel et al. 2003); <http://leda.univ-lyon1.fr>.

Table 3. Prominent Galaxies in the Fornax Cluster centre, showing published data together with our calculations of galaxy masses and tidal radii. FCC numbers, B_T magnitudes and effective radii are from the Fornax Cluster Catalogue (Ferguson 1989). Central velocity dispersions (σ) are from HyperLEDA, unless (shown in *italics*) they are estimated as explained in the text. Coordinates (J2000) and heliocentric recessional velocities are from NED, except that we have obtained NGC 1399’s recessional velocity from Richtler et al. (2004). Morphological types are from HyperLEDA.

Catalogue	Identifier	B_T	R_{eff}	σ	R.A.	Dec.	cz	Type	Mass	r_t	
NGC	FCC	<i>mag</i>	<i>arcsec</i>	<i>km s⁻¹</i>	<i>h:m:s</i>	<i>d:m:s</i>	<i>km s⁻¹</i>		$M_{sol} \times 10^{10}$	<i>kpc</i>	<i>arcsec</i>
1399	213	10.6	37.2	342	03:38:29.08	-35:27:02.7	1442±9	E0	~600 ^a		
1365	121	10.2	130.0	151	03:33:36.37	-36:08:25.4	1636±1	Sb	5.5	68	627
PGC013230	136	14.8	16.3	153	03:34:29.48	-35:32:47.0	1205±1	S0	1.9	24	301
1373	143	14.3	11.8	70	03:34:59.21	-35:10:16.0	1334±2	E	0.3	14	156
1374	147	11.9	24.0	186	03:35:16.59	-35:13:34.5	1294±2	E	4.5	29	338
1375	148	13.6	26.9	69	03:35:16.82	-35:15:56.4	740±6	S0	0.4	7	148
IC0335	153	13.0	11.3	78	03:35:31.04	-34:26:49.4	1619±6	S0	0.5	29	270
1379	161	11.7	20.9	121	03:36:03.95	-35:26:28.3	1324±2	E	1.7	15	174
1380	167	11.3	39.8	221	03:36:27.58	-34:58:33.6	1877±12	S0	15.4	58	464
1381	170	13.0	12.9	152	03:36:31.68	-35:17:42.7	1724±9	S0	2.2	19	164
1369	176	13.7	26.0	88	03:36:45.25	-36:15:22.4	1414±17	S0-a	3.5	37	394
1380A	177	13.2	12.6	67	03:36:47.49	-34:44:22.6	1561±6	S0	0.4	18	169
1386	179	12.4	50.0	166	03:36:46.22	-35:59:57.3	868±5	S0-a	5.0	19	329
PGC013343	182	14.9	11.4	62	03:36:54.32	-35:22:29.0	1657±19	E-S0	0.3	7	66
1387	184	12.3	50.1	143	03:36:57.06	-35:30:23.9	1302±12	E-S0	6.2	15	172
1380B	190	13.5	16.3	95	03:37:08.96	-35:11:42.1	1740±17	E-S0	1.1	13	113
1389	193	12.8	20.1	139	03:37:11.74	-35:44:46.0	921±12	E-S0	1.5	8	134
1396	202	15.3	9.8	69	03:38:06.54	-35:26:24.4	808±22	E-S0	0.2	1	12
ESO358-042	203	15.5	13.0	47	03:38:09.15	-34:31:06.7	1138±28	S0	1.4	23	309
PGC074808	207	15.9	8.5	41	03:38:19.27	-35:07:44.7	1420±20	S0-a	1.1	9	100
PGC074806	208	17.3	11.7	25	03:38:18.71	-35:31:52.1	1720±50	E-S0	1.9	4	32
PGC074811	211	16.3	5.6	36	03:38:21.52	-35:15:34.1	2325±15	E-S0	1.2	9	61
1404	219	10.9	20.0	232	03:38:51.92	-35:35:39.8	1947±4	E	8.8	13	100
PGC013449	222	15.6	14.5	45	03:39:13.36	-35:22:18.6	824±24	S0	1.1	3	52
1427A	235	13.4	36.3	98	03:40:09.30	-35:37:28.0	2028±1	Irr	7.0	29	215
ESO358-051	263	14.6	20.5	64	03:41:32.60	-34:53:18.0	1724±6	S0-a	3.3	43	373
PGC074933	274	16.5	12.0	33	03:42:17.30	-35:32:27.0	1073±76	E-S0	1.2	18	246
1427	276	11.8	32.4	162	03:42:19.43	-35:23:33.5	1388±3	E	4.9	36	395
1428	277	13.8	10.1	85	03:42:22.73	-35:09:14.4	1640±8	E-S0	1.6	32	292
ESO358-054	285	14.2	28.7	-	03:43:02.19	-36:16:24.1	886±3	SABd	0.02	5	92

a. The mass of NGC 1399 is estimated from X-ray emission (Jones et al. 1997).

For several of these galaxies, we can compare our tidal radius calculations to published GC radial distribution limits⁶ estimated from deep photometry. For NGC 1379 and NGC 1387, our tidal radii agree with the estimated GC limits of 162 and 186 arcsec respectively (Bassino, Richtler & Dirsch 2006b). For NGC 1374, NGC 1380 and NGC 1427, our tidal radii are significantly greater than the estimated GC limits of respectively 132 arcsec (Bassino et al. 2006b), 250–300 arcsec (Forte et al. 2001) and 200 arcsec (Kissler-Patig et al. 1997) – in these cases we suggest that the GC radial extent is not being tidally truncated by NGC 1399. For NGC 1404, which is within NGC 1399’s X-ray halo, there are published GC limits of approximately 200 arcsec (Richtler et al. 1992) and 240 arcsec (Forbes et al. 1997) – at least two times our calculated tidal radius. However, the allocation of bound CSS would not be altered if we doubled our calculated tidal radius for NGC 1404.

CSS within or near to the tidal radius of prominent galaxies other than NGC 1399 are indicated by entries in the last two columns of Table 2. We then apply an escape velocity filter to these provisionally identified bound CSS. In the absence of secondary distance indicators, redshift-derived recessional velocity is a combination of two unknowns – peculiar velocity and distance. Since we have redshift information

rather than true distances, we assume that a CSS is as close as possible in real space to its associated prominent galaxy, having a real spatial separation equal to the sky-projected separation – this maximises the gravitational binding force and consequent escape velocity. A CSS and its associated galaxy are assumed to be gravitationally bound if their recessional velocities differ by less than the escape velocity $v_{esc} = (2GM_{galaxy}/r)^{1/2}$ at their projected radial spatial separation r . The final column of Table 2 lists the ratio of the recessional velocity difference (between the CSS and its potentially associated galaxy) and the escape velocity at the projected radius. Therefore a ratio less than 1 implies they are gravitationally bound.

By this method we suggest that 11 of the redshift-confirmed CSS can be confidently associated with cluster galaxies other than NGC 1399, and we exclude them in our following analysis. Fig. 7 shows the projected positions of redshift-confirmed CSS and prominent cluster galaxies surrounding NGC 1399, overlaid with the VLT-FLAMES field boundaries and the tidal radii of prominent galaxies. Three prominent galaxies that have bound CSS are labelled.

4 ANALYSIS AND DISCUSSION

Having eliminated CSS bound to prominent cluster galaxies other than NGC 1399, we analyse the radial density distribution, recessional velocity distribution and colour-magnitude relation of the remaining unbound CSS, using the combined

⁶ GC radial distribution limits are defined to be where the projected radial profile of GC number density falls to the observed background level.

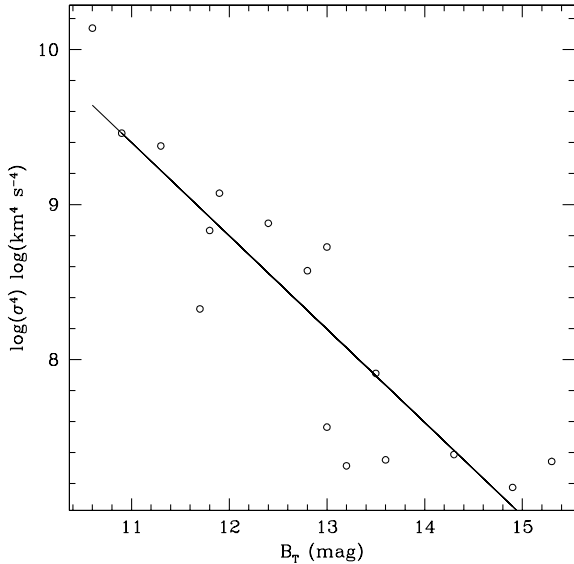


Figure 6. Correlation of B_T mag with measured central velocity dispersion (σ) for 16 prominent galaxies (open circles) surrounding NGC 1399. The correlation relation is shown as a continuous line.

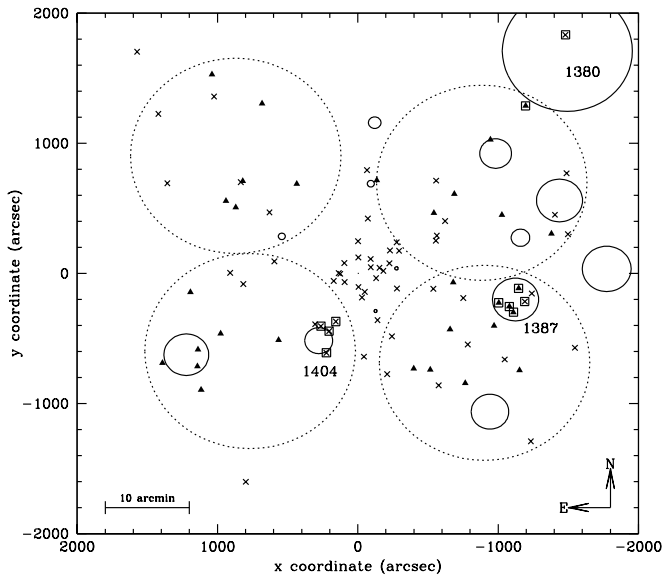


Figure 7. CSS surrounding NGC 1399 (centre) from spectroscopy with 2dF (crosses; Drinkwater et al. 2000b; Gregg et al. 2007) and VLT-FLAMES (solid triangles), overlaid with our four 25-arcminute diameter VLT-FLAMES fields (dotted circles). We show the projected tidal radii (unfilled circles) of prominent cluster galaxies – CSS considered to be gravitationally bound to these galaxies are enclosed within squares. Our wide-field spectroscopy provides new data between the redshift-confirmed Dirsch et al. (2004) GCs which extend to 9 arcminutes from NGC 1399, and the wide-field photometry of Bassino et al. (2006a) who estimates the extent of NGC 1399’s GC system at 45 ± 5 arcminutes.

Table 4. Radial Surface Density Distribution of observed CSS around NGC 1399, with approximately equal numbers of CSS in each varying width radial bin.

Distance from NGC 1399 arcmin	Area in VLT Fields arcmin ²	Observed Unbound CSS	Observed Number Density arcmin ⁻²	Completeness per cent	Estimated Number Density ^a arcmin ⁻²
4.0-12.5	287	9	0.031	8.9	0.36 ± 0.12
12.5-15.2	212	10	0.047	12.5	0.38 ± 0.12
15.2-18.84	344	9	0.026	15.9	0.16 ± 0.05
18.84-24.2	566	9	0.016	21.3	0.07 ± 0.02
24.2-34.0	541	9	0.017	29.2	0.06 ± 0.02
1950		46			

a. Uncertainties are based on Poisson statistics.

data from 2dF (Drinkwater et al. 2000b; Gregg et al. 2007) and VLT-FLAMES. We separate the unbound CSS into two sub-populations – brighter or fainter than the metallicity and kinematic break found by Mieske et al. (2004, 2006) at $M_V = -11$.

We also compare the unbound CSS data to previously published data for NGC 1399’s GC system and dwarf galaxies in the central region of the Fornax Cluster. For the spectroscopic surveys where individual object coordinates are available (Dirsch et al. 2004; Drinkwater et al. 2000b; Bergond et al. 2007; Gregg et al. 2007), we convert to CTIO $g'r'i'$ photometry (Karick et al. 2007) by matching object positions in both catalogues. No coordinates were available for the 160 NGC 1399 GCs spectroscopically identified by Schubert et al. (2004), so we were unable to compare our results in detail to this data. For candidate GCs derived from large sample photometric datasets, we use $g' = V + 0.3$ (where $20.3 < g' < 25.7$) for the Dirsch et al. (2003) survey, and $g' = T_1 - 0.2$ (where $20.3 < g' < 25.7$) for the Bassino et al. (2006a) survey.

4.1 Projected radial distribution

The projected distribution of unbound CSS (see Fig. 7) appears anisotropic with respect to NGC 1399 – the major axis (best-fitting line through the projected distribution) of unbound CSS is rotated $84 \pm 5^\circ$ from N through E. This is not an artefact of the incomplete field coverage of our VLT-FLAMES observations, since the 2dF-derived CSS (covering the entire field shown in Fig. 7) displays the same projected distribution.

Table 4 tabulates the radial surface density distribution of unbound 2dF and VLT-FLAMES CSS located within the VLT field boundaries. The radial bins are set to contain approximately equal numbers of targets within our VLT-FLAMES fields, which extend radially between 4 and 34 arcminutes from NGC 1399. Completeness percentages compare the total number of accepted redshifts (from 2dF and VLT-FLAMES observations) to the total number of potential point sources targets, in each radial range of our VLT-FLAMES fields.

In order to compare our unbound CSS radial density profile to previously published results by Bassino et al. (2006a), we used their combined blue and red GC number density data (Table 2 in their paper) between 9.5 and 28 arcmin from NGC 1399, as our VLT-FLAMES data only

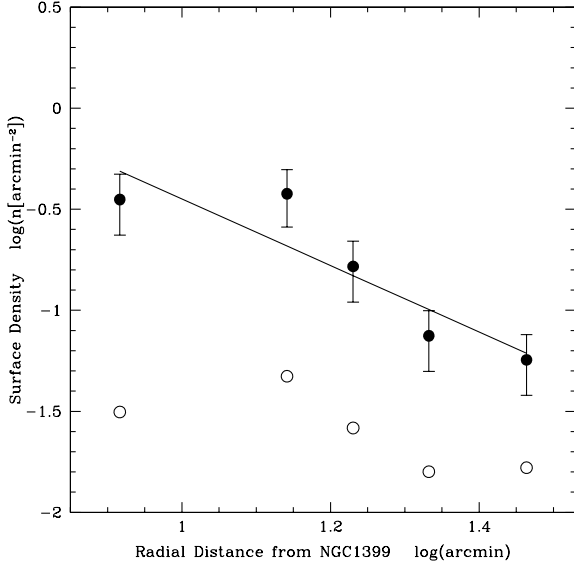


Figure 8. Radial surface density distribution of unbound 2dF/VLT-derived CSS located within the VLT fields. The original data and completeness-adjusted estimates are shown as open and filled circles respectively. The best-fitting line for the completeness-adjusted data has a slope of -1.6 ± 0.2 .

have significant areal coverage within these radial limits. Similarly, from Table 3 in Dirsch et al. (2003) we used the combined blue and red GC number density between approximately 8 and 23 arcmin (0.94 and 1.36 in logarithmic units). Fig. 8 shows that the best-fitting line to our completeness-adjusted surface density data ($18.6 < g' < 22.9$) has a slope of -1.6 ± 0.2 in log-log space. Within this radial range our result is similar to the slope of -1.7 (Bassino et al. 2006a) from photometry of candidate NGC 1399 GCs in a similar magnitude range ($19.8 < g' < 22.8$), and the slope of -1.5 (Dirsch et al. 2003) from photometry of fainter candidate GCs ($23.3 < g' < 25.7$).

4.2 Recessional velocity distribution

In Table 5 we compare the heliocentric recessional velocity data from our observations with other published sources, and in Fig. 9 we show a velocity histogram comparing the unbound 2dF/VLT-FLAMES CSS to NGC 1399's inner GCs (2 to 9 arcminutes from NGC 1399; Dirsch et al. 2004).

The mean recessional velocity of the radially extended 2dF/VLT-FLAMES CSS differs by only $\sim 20 \text{ km s}^{-1}$ from that of NGC 1399's inner GC system. A *t*-test shows this difference is marginally significant (50 per cent probability that they are drawn from the same population distribution). However, the CSS velocity dispersion is $\sim 80 \text{ km s}^{-1}$ less than that of the NGC 1399 inner GCs. An *F*-test shows this difference to be highly significant, implying that the CSS and GC populations are kinematically different (0.1 per cent probability that they are drawn from the same population distribution). The CSS velocity dispersion is also $\sim 50 \text{ km s}^{-1}$ less than that reported by Schubert et al. (2004) for the more extended GC system (8 to 18 arcminutes from NGC 1399).

Table 5. Heliocentric Recessional Velocity Summary

	Source	N	Mean km s^{-1}	Std. Devn. km s^{-1}
NGC 1399	Richtler et al. (2004)	1	1442 ± 9	—
Inner GCs	Richtler et al. (2004) ^a	491	1445 ± 14	303 ± 10
Outer GCs	Schubert et al. (2004)	160	—	~ 276
Faint CSS	2dF/VLT ($M_V \geq -11$)	66	1464 ± 28	225 ± 20
Bright CSS	2dF/VLT ($M_V < -11$)	14	1464 ± 61	229 ± 45
All CSS	2dF/VLT	80	1464 ± 25	224 ± 16
Early-type Dwarfs	various sources ^b	88	1487 ± 39	365 ± 28

a. analysis based on Dirsch et al. (2004) sample.

b. Early-type galaxies selected from FCC catalogue (Ferguson 1989) with dwarf absolute magnitudes ($M_B > -17.6$) and with available recessional velocities. Sources for recessional velocities are as follows: Drinkwater et al. (2000a, 2001); Mieske et al. (2002); Karick (2005)

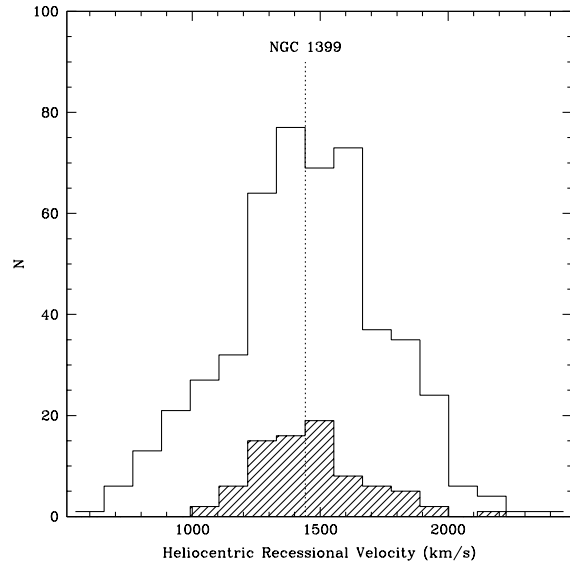


Figure 9. The heliocentric recessional velocities of 2dF/VLT CSS not gravitationally bound to prominent galaxies surrounding NGC 1399 (hatched histogram) are compared with NGC 1399's inner GC system (Dirsch et al. 2004) and with NGC 1399 itself (vertical dotted line).

Similarly, there is only a small difference between the mean velocities of unbound CSS and early-type dwarf galaxies in the central region of the Fornax Cluster (63 per cent *t*-test probability that they are from the same population), but a large difference in velocity dispersions (< 0.005 per cent *F*-test probability that they are from the same population).

The difference in mean recessional velocities of the bright ($M_V < -11$) and faint sub-populations of CSS is negligible, as confirmed by a *t*-test (> 99 per cent probability that they are from the same population). The difference in their velocity dispersions is also negligible, as confirmed by an *F*-test (86 per cent probability that they are from the same population).

Fig. 10 compares the radial variation in heliocentric recessional velocity of bright and faint CSS with that of NGC

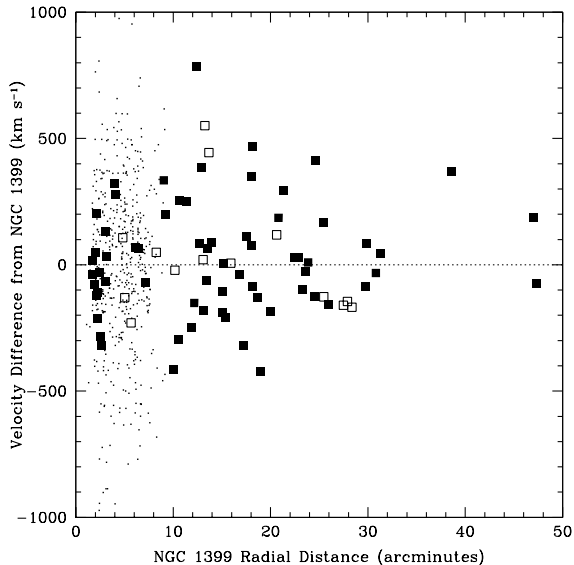


Figure 10. Variation with radial distance from NGC 1399 in the heliocentric recessional velocity of bright ($M_V < -11$; open squares) and faint (filled squares) 2dF/VLT CSS, and of NGC 1399's inner GC system (Dirsch et al. (2004); small dots). The horizontal dotted line shows NGC 1399's recessional velocity.

1399's inner GCs. The maximum radial extent of the bright CSS is ~ 28 arcmin from NGC 1399, whereas the faint CSS extend to ~ 47 arcmin. No radial trend is apparent in these data for either sub-population.

We estimate the group rotation of unbound CSS around NGC 1399 by using a non-linear least squares fit of their position angles (θ_i with respect to NGC 1399) and recessional velocities (v_i). The fitted function is of the form $v_i = v_{sys} + A \sin(\theta_i - \theta_0)$, where v_{sys} is the mean velocity of the CSS, A is the rotation amplitude and θ_0 the position angle of the rotating system (measured from N through E). For the outermost blue GC clusters between 6 and 9 arcmin from NGC1399, Richtler et al. (2004) found a rotation amplitude of $68 \pm 60 \text{ km s}^{-1}$ and a position angle of $141^\circ \pm 39^\circ$. With Monte-Carlo simulation, we find a mean unbound CSS recessional velocity of $1472 \pm 1 \text{ km s}^{-1}$ (close to that of NGC 1399), rotation amplitude of $75 \pm 1 \text{ km s}^{-1}$ (similar to Richtler et al. 2004) and rotational position angle of $34^\circ \pm 10^\circ$.

4.3 Colour distribution

Fig. 11 shows the colour-magnitude distribution of VLT/2dF-derived unbound CSS and NGC 1399's inner GC system. No colour bimodality is apparent or expected in our CSS data – in the magnitude range $20 < r' < 21$ Dirsch et al. (2003) finds that GC colours are unimodal, and Bassino et al. (2006a) has confirmed this for more radially extended CSS. The bimodal ‘red’ and ‘blue’ faint ($r' \geq 21$) GC sub-populations clearly found by Dirsch et al. (2004) are also not discernible in our more radially extended faint CSS data, probably because our $g' - i'$ colour index is less sensitive to metallicity than their Washington $C - T1$ colour index. The ‘blue tilt’ has not been previously detected in

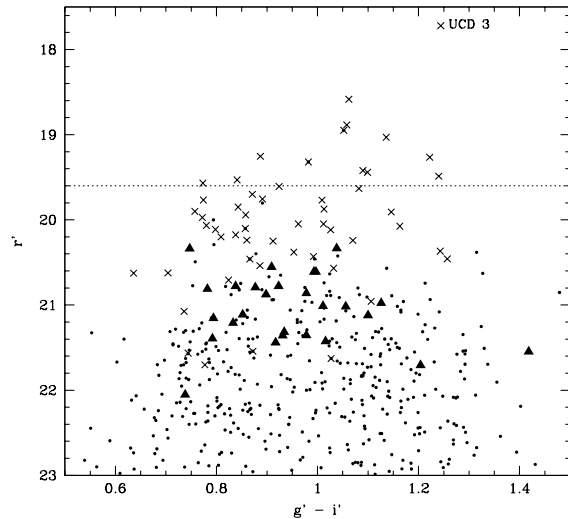


Figure 11. Colour-magnitude plot of redshift-confirmed unbound CSS in the Fornax galaxy cluster. Previously catalogued (crosses) and newly-discovered CSS (filled triangles) are compared with NGC 1399 GCs (small dots) from Dirsch et al. (2004). The dotted horizontal line divides the bright and faint CSS according to the metallicity break at $M_V = -11$ ($r' = 19.6$) found by Mieske et al. (2006). UCD 3 is a known, particularly bright and extended object.

NGC 1399's GC system, and is also not apparent in our CSS data.

The mean colour index ($g' - i' = 1.13 \pm 0.33$) of the 11 CSS bound to prominent galaxies (not shown in Fig. 11) is redder than that of the 80 unbound CSS ($g' - i' = 0.94 \pm 0.19$). This implied higher metallicity is expected for bound CSS which are closer to their parent galaxies (for example Brodie & Strader 2006), although Barmby et al. (2007) finds this correlation to be weak in galaxies of the Local Group. Excluding UCD 3 which may be a dwarf galaxy (de Propris et al. 2005), the mean colour index of the bright unbound CSS ($g' - i' = 1.04 \pm 0.14 \text{ mag}$) is also slightly redder than that of the faint unbound CSS ($g' - i' = 0.92 \pm 0.19 \text{ mag}$), as might be expected given their higher metallicity (see Mieske et al. 2006).

Fig. 12 shows the $g' - i'$ colour index values of the bright and faint CSS as a function of radial distance from NGC 1399. There is no significant trend with increasing radius.

5 SUMMARY

CSS are potential trace particles of galaxy assembly and observable fossil evidence of cluster evolution. The origin of bright CSS is unclear – they may be the bright tail of the GC distribution, merged superstellar clusters formed in galaxy interactions, or the tidally-stripped remnants of nucleated dwarf galaxies. The Fornax Cluster is a prime nearby target to systematically map the distribution of CSS over a large area with multi-fibre spectroscopy. While 2dF mapping (Drinkwater et al. 2000a; Gregg et al. 2007) of the brighter radially-dispersed CSS has been completed within a 1° ra-

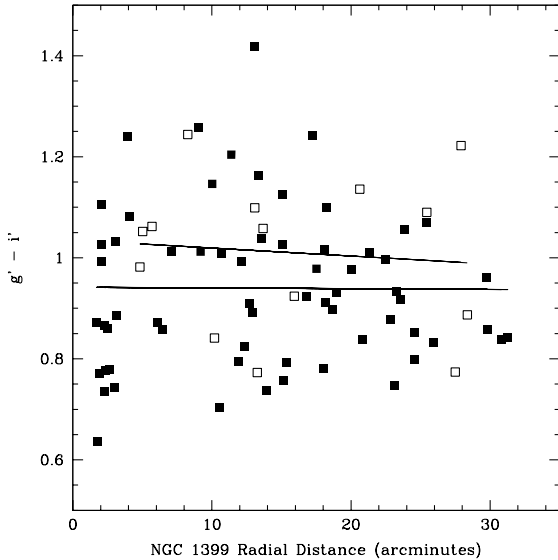


Figure 12. We show $g' - i'$ colours of the bright ($M_V < -11$; open squares) and faint (filled squares) CSS as a function of radial distance from NGC 1399. The best-fitting lines for the bright (upper line) and faint (lower line) systems indicate insignificant radial colour change.

dus around NGC 1399, extended exposure times or larger light-gathering power are needed to obtain reliable redshifts at the typical magnitudes of fainter CSS (see Fig. 3).

As Fig. 13 illustrates, our VLT-FLAMES observations extend the faint limits of more widely dispersed CSS, and improve the recessional velocity accuracy of redshift-confirmed CSS in the central region of the Fornax Cluster. We have improved redshift accuracy for 23 known CSS and 3 member galaxies, obtained the first spectroscopic redshift measurement for member galaxy FCC 171, and measured redshifts for 30 new CSS. Our redshift results also establish significantly tighter target selection criteria, which we estimate could increase the yield of faint Fornax CSS to ~ 45 per cent in future observations.

After excluding from our analysis 11 CSS dynamically associated with prominent galaxies surrounding NGC 1399, we are left with a catalogue of 80 redshift-confirmed unbound CSS surrounding NGC 1399. The following findings relate to these 80 unbound CSS (a sufficiently large data set to overcome small number statistics) unless otherwise stated

(i) CSS are mostly located off the main stellar locus in colour-colour space, suggesting that they have a significant red stellar population component rather than being dominated by young blue stars.

(ii) The projected distribution of unbound CSS about NGC 1399 is anisotropic, following the galaxy distribution within the Cluster, and there is weak evidence for group rotation about NGC 1399.

(iii) The completeness-adjusted radial surface density profile of 46 spectroscopically-confirmed CSS located in our four VLT-FLAMES fields has a slope of -1.7 ± 0.2 in log-log space. This result is similar to the slope of -1.6 (Bassino et al. 2006a) for photometry-derived candidate NGC 1399 GCs in a similar magnitude range, and the

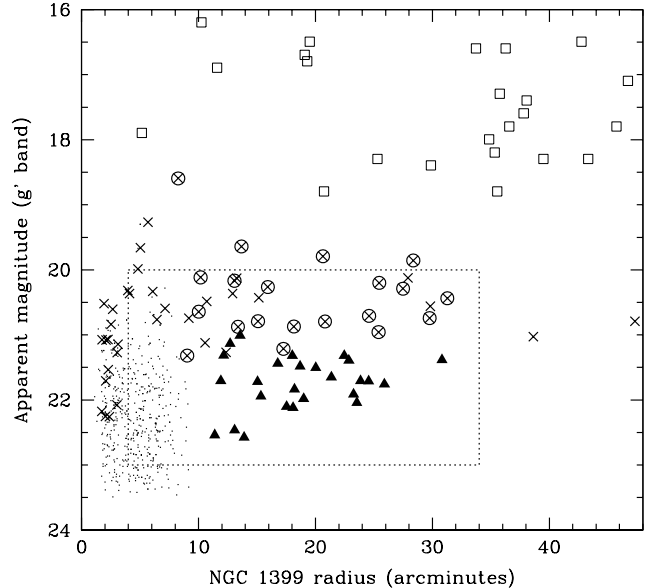


Figure 13. The g' -band magnitude and radial distance of redshift-confirmed CSS from NGC 1399. We show NGC 1399's inner GCs (dots) from Dirsch et al. (2004), and the more radially extended CSS from observations with 2dF (crosses) and VLT-FLAMES (solid triangles). CSS from 2dF observations which have been reconfirmed with VLT-FLAMES are circled. Early-type dwarf galaxies (open squares) are compiled from various sources as noted in Table 5. The approximate limits of our VLT-FLAMES data are shown as a dotted line box – 4 brighter 2dF-derived CSS were also targeted for redshift reconfirmation.

slope of -1.5 from Dirsch et al. (2003) photometry of fainter candidate GCs. However, due to binning (of a smaller data set in this case), our result is subject to uncertainty from small number statistics.

(iv) The CSS mean heliocentric recessional velocity ($1464 \pm 25 \text{ km s}^{-1}$) is between that of NGC 1399's inner GC system and that of the surrounding dwarf galaxies, but the CSS velocity dispersion is approximately $80\text{--}140 \text{ km s}^{-1}$ lower than for these other cluster populations.

(v) The mean colour of 14 bright CSS ($M_V < -11$) is 0.1 mag redder than the 66 faint CSS, suggesting they may have higher metallicity, subject to the uncertainty caused by small number statistics.

(vi) CSS show no significant trend in $g' - i'$ colour index with radial distance from NGC 1399.

6 ACKNOWLEDGEMENTS

This work has been supported by grant No. AST0407445 from the National Science Foundation. Part of the work reported here was done at the Institute of Geophysics and Planetary Physics, under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. Evstigneeva and Drinkwater acknowledge support from the Australian Research Council.

REFERENCES

- Barmby P., McLaughlin D., Harris W., Harris G., Forbes D., 2007, *AJ*, 133, 2764
- Bassino L., Cellone S., Forte J., Dirsch B., 2003, *A&A*, 399, 489
- Bassino L., Faifer F., Forte J., Dirsch B., Richtler T., Geisler D., Schuberth Y., 2006a, *A&A*, 451, 789
- Bassino L., Richtler T., Dirsch B., 2006b, *MNRAS*, 367, 156
- Bekki K., Couch W., Drinkwater M., 2001, *ApJ*, 552, L105
- Bekki K., Couch W., Drinkwater M., Shioya Y., 2003a, *MNRAS*, 344, 399
- Bekki K., Forbes D., Beasley M., Couch W., 2003b, *MNRAS*, 344, 1334
- Belokurov V., et al., 2007, *ApJ*, 654, 897
- Bergond G., Zepf S., Romanowsky A., Sharples R., Rhode K., 2006, *A&A*, 448, 155
- Bergond G., et al., 2007, *A&A*, 464, L21
- Bertin E., Arnouts S., 1996, *A&AS*, 117, 393
- Binney J., Tremaine S., 1987, *Galactic Dynamics*. Princeton University Press, Princeton, NJ
- Blakeslee J., 2000, in F. Durret Gerbal D., eds, *Proc. IAP 2000, Constructing the Universe with Clusters of Galaxies. Huddled masses yearning to stream free: Globular clusters in the hearts of galaxy clusters*. Institut d'Astrophysique de Paris, Paris, France, p. 61B
- Brodie J., Strader J., 2006, *ARA&A*, 44, 193
- Carretta E., Gratton R., Clementini G., Fusi-Pecchi F., 2000, *ApJ*, 533, 215
- de Propris R., Phillipps S., Drinkwater M., Gregg M., Jones J., Evstigneeva E.A., Bekki K., 2005, *ApJ*, 623, L105
- Dirsch B., Richtler T., Geisler D., Forte J., Bassino L., Gieren W., 2003, *AJ*, 125, 1908
- Dirsch B., et al., 2004, *AJ*, 127, 2114
- Drinkwater M., et al., 2000a, *A&A*, 355, 900
- Drinkwater M., Jones J., Gregg M., Phillipps S., 2000b, *PASA*, 17, 227
- Drinkwater M., Gregg M., Holman B., Brown M., 2001, *MNRAS*, 326, 1076
- Drinkwater M., Gregg M., Couch W., Ferguson H., Jones M. H. J., Karick A., Phillipps S., 2004, *PASA*, 21, 375
- Fellhauer M., Kroupa P., 2002, *MNRAS*, 330, 642
- Ferguson H., 1989, *AJ*, 98, 367
- Forbes D., Grillmair C., Williger G., Elson R., Brodie J., 1997, *MNRAS*, 293, 325
- Forte J., Geisler D., Ostrov P., Piatti A., Gieren W., 2001, *AJ*, 121, 1992
- Gregg M., et al., 2007, *AJ*, submitted
- Hasegan M., et al., 2005, *ApJ*, 627, 203
- Hilker M., Infante L., Vieira G., Kissler-Patig M., Richtler T., 1999a, *A&AS*, 134, 75
- Hilker M., Kissler-Patig M., Richtler T., Infante L., Quintana H., 1999b, *A&AS*, 134, 59
- Jacoby G., Hunter D., Christian C., 1984, *ApJS*, 56, 257
- Jones C., Stern C., Forman W., Breen J., David L., Tucker W., Franx M., 1997, *ApJ*, 482, 143
- Karick A., 2005, PhD thesis, Univ. Melbourne
- Karick A., Drinkwater M., Gregg M., 2003, *MNRAS*, 344, 188
- Karick A., Drinkwater M., Gregg M., 2007, *AJ*, submitted
- Kissler-Patig M., Richtler T., Storm J., Valle M. D., 1997, *A&A*, 327, 503
- Kravtsov A., Gnedin O., Klypin A., 2004, *ApJ*, 609, 482
- Marston C., Bastian N., Saglia R., Kissler-Patig M., Schweizer F., P. Goodfroom 2004, *A&A*, 416, 467
- Mieske S., Hilker M., Infante L., 2002, *A&A*, 383, 823
- Mieske S., Hilker M., Infante L., 2004, *A&A*, 418, 445
- Mieske S., Hilker M., Infante L., Jordán A., 2006, *AJ*, 131, 2442
- Moore B., Lake G., Quinn T., Stadel J., 1999, *MNRAS*, 304, 465
- Moore B., Diemand J., Madau P., Zemp M., Stadel J., 2006, *MNRAS*, 368, 563
- Padmanabhan N., et al., 2004, *New Astronomy*, 9, 329
- Paturel G., Petit C., Prugniel P., Theureau G., Rousseau J., Brouty M., Dubois P., Cambrésy L., 2003, *A&A*, 412, 45
- Phillipps S., Drinkwater M., Gregg M., Jones J., 2001, *ApJ*, 560, 201
- Press W., et al., 1992, *Numerical Recipes in C*. Second Edition. Cambridge University Press, Cambridge
- Richtler T., Grebel E., Domgörgen H., Hilker M., Kissler M., 1992, *A&A*, 264, 25
- Richtler T., Drenkhahn G., Gómez M., Seggewiss W., 2000, in Bergeron J., Renzini A., eds, *Proc. ESO Symp., From Extrasolar Planets to Cosmology: The VLT Opening Symposium. The Hubble Constant from the Fornax Cluster Distance*. Springer-Verlag, Berlin, p. 259
- Richtler T., et al., 2004, *AJ*, 127, 2094
- Schuberth Y., Richtler T., Dirsch B., Hilker M., Larsen S., 2004, in Dettmar R., Klein U., Salucci P., eds, *Baryons in Dark Matter Halos, Proceedings of Science. Kinematics of the Outer Cluster System of NGC 1399*. SISSA, Proceedings of Science, Trieste, Italy, p. 65
- Stetson P., 2000, *PASA*, 112, 925
- Tonry J., Davis M., 1979, *AJ*, 84, 1511
- West M., Côté P., Jones C., Forman W., Marzke R., 1995, *ApJ*, 453, L77

Table 2. Bound and Unbound CSS. Coordinates (J2000) and de-reddened photometry are from recalibrated CTIO imaging (Karick et al. 2007). The stellarity index (sgc-r), derived by SExtractor from r' band photometry (Karick 2005; Karick et al. 2007), compares the target light profile to a point-spread function (0 extended object; 1 point source). Velocities (cz) are heliocentric recessional. 2dF revised velocity data are derived from Drinkwater et al. (2000b) and Gregg et al. (2007). FCOS data are from the Fornax Compact Object Survey (Mieske et al. 2004). Bergond data are from VLT-FLAMES spectroscopy (Bergond et al. 2006). R -values shown in brackets are from the previously published redshift measurement with the lowest error margin.

R.A. <i>h m s</i> (1)	Dec. <i>d m s</i> (2)	<i>g'</i> <i>mag</i> (3)	<i>r'</i> <i>mag</i> (4)	<i>i'</i> <i>mag</i> (5)	sgc-r (6)	2dF <i>km s</i> ^{−1} (7)	FCOS ^b <i>km s</i> ^{−1} (8)	Bergond <i>km s</i> ^{−1} (9)	VLT-FLAMES <i>km s</i> ^{−1} <i>R</i> -value. (10) (11)		Allocation Galaxy $[\Delta v]/v_{esc}$ (12) (13)		
Known Fornax Cluster Galaxies													
03 36 37.25	−35 23 09.4	20.87	20.34	20.12	0.38				1401±13	3.6	FCC 171		
03 37 17.91	−35 41 57.6	20.55	19.93	19.65	0.00	1237±84			1279±13	3.7	FCC 194		
03 39 13.30	−35 22 17.2	19.20	18.54	18.20	0.03		824±24		794±6	9.9	FCC 222		
03 40 23.54	−35 16 36.5	20.52	19.89	19.60	0.03	2045±107			1814±11	4.0	FCC 241		
Known Fornax Cluster CSS													
03 36 22.23	−35 36 34.4	20.29	19.77	19.51	0.98	1462±76			1282±10	5.7			
03 36 26.67	−35 22 01.5	20.20	19.42	19.11	0.05 ^c	1499±117			1315±8	6.6	NGC 1381	4.1	
03 36 27.69	−35 14 14.0	20.12	19.27	18.90	0.95	1297±45		1386±4		(29.6)	NGC 1381	3.4	
03 36 28.74	−34 56 29.9	21.95	21.48	21.34	0.83	1658±65				(4.6)	NGC 1380	0.6 ^a	
03 36 34.32	−35 19 32.6	20.71	20.11	19.91	0.98	1817±104		1861±5	1856±9	5.5	NGC 1381	1.3	
03 36 47.58	−35 29 37.1	20.79	20.18	19.96	0.98	1446±89			1628±7	6.7	NGC 1387	1.7	
03 36 47.69	−35 48 34.0	20.74	20.05	19.78	0.98	1340±90			1358±11	4.2			
03 36 51.63	−35 30 39.1	20.78	20.14	19.87	0.96	1375±46			1462±7	6.5	NGC 1387	0.8 ^a	
03 37 03.23	−35 38 04.7	19.79	19.03	18.66	0.94	1491±39	1571±75	1551±5	1561±3	20.9			
03 37 24.83	−35 36 10.0	20.26	19.61	19.34	0.98	1496±55			1448±4	13.3			
03 37 41.77	−35 41 23.2	21.21	20.37	19.97	0.98	1175±61	1025±60		1122±5	9.4			
03 37 43.49	−35 15 10.2	20.79	20.12	19.76	0.98	1641±99	1240±89		1255±6	9.9			
03 37 43.56	−35 22 51.8	20.12	19.53	19.28	0.98	1326±82		1419±11	1420±7	8.8			
03 38 09.21	−35 35 07.3	21.32	20.46	20.06	0.98	1806±58		1773±22	1776±6	7.5			
03 38 11.95	−35 39 57.5	20.88	20.08	19.71	0.98	1307±63	1300±45		1381±6	9.2			
03 38 17.97	−35 15 06.4	21.31	20.61	20.32	0.98		1401±264		1291±11	4.3	PGC 074811	9.8	
03 38 23.73	−35 13 49.8	20.13	19.57	19.36	0.98	1993±199	1553±72			(3.3)	PGC 074811	7.3	
03 38 41.94	−35 33 13.0	20.23	19.46	19.20	0.98	2080±148			2010±5	9.3	NGC 1404	0.3 ^a	
03 38 45.80	−35 34 26.6	22.12	20.74	20.37	0.04 ^c	1845±87				(3.50)	NGC 1404	0.4 ^a	
03 38 47.41	−35 37 13.6	20.75	19.96	19.62	0.87	1893±68				(4.44)	NGC 1404	0.2 ^a	
03 38 50.64	−35 33 48.4	21.82	20.80	20.26	0.07 ^c	1887±105				(3.77)	NGC 1404	0.8 ^a	
03 38 54.05	−35 33 33.6	18.59	17.72	17.35	0.03 ^d	1591±36	1493±61		1491±2	24.0	NGC 1404	1.9	
03 39 17.67	−35 25 30.2	20.64	19.91	19.50	0.98	1022±46	980±45	1027±8	1026±5	11.0			
03 39 20.49	−35 19 14.4	20.17	19.44	19.07	0.94	1420±64	1341±57		1462±5	10.4			
03 39 35.90	−35 28 24.6	19.64	18.89	18.58	0.70	1920±40	1848±85	1878±5	1886±3	16.7			
03 39 37.16	−35 15 21.9	20.87	20.25	19.96	0.98	1800±93	1921±114		1912±6	8.3			
03 39 52.54	−35 04 24.2	19.86	19.25	18.97	0.68	1355±72			1274±4	14.1			
03 40 19.89	−35 15 30.0	20.96	20.24	19.89	0.98	1650±74			1608±6	8.6			
03 40 24.92	−35 06 37.5	20.44	19.85	19.60	0.98	1432±59			1489±11	4.6			
New Fornax Cluster CSS													
03 36 36.31	−35 21 58.6	22.04	21.44	21.13	0.98				1415±44	3.0			
03 36 51.67	−35 05 35.1	21.39	20.92	20.70	0.98				1869±20	3.2	NGC 1380	0.1 ^a	
03 36 54.57	−35 39 26.9	21.39	20.79	20.52	0.98				1469±10	5.1			
03 36 55.24	−35 28 57.6	22.89	22.00	21.69	0.97				1273±14	3.1	NGC 1387	0.2 ^a	
03 36 58.21	−35 32 01.6	22.48	21.65	21.40	0.98				1327±11	3.5	NGC 1387	0.1 ^a	
03 37 00.64	−35 31 17.6	22.66	21.89	21.38	0.97				1337±10	4.9	NGC 1387	0.2 ^a	
03 37 05.15	−35 19 34.2	21.48	20.88	20.58	0.98				1312±10	4.7			
03 37 06.84	−35 30.48.8	22.90	22.18	21.75	0.98				1258±12	3.2	NGC 1387	0.2 ^a	
03 37 09.48	−35 33 45.5	22.10	21.36	21.12	0.97				1555±11	4.0			
03 37 12.05	−35 09 55.1	21.91	21.32	20.98	0.97				1345±13	3.0	NGC 1380B	4.7	
03 37 26.23	−35 41 06.1	21.98	21.36	21.05	0.98				1018±14	3.2			
03 37 32.93	−35 16 52.0	21.94	21.39	21.15	0.98				1234±16	3.6			
03 37 33.45	−35 28 12.8	22.54	21.71	21.33	0.98				1692±15	3.4			
03 37 35.24	−35 34 12.9	22.46	21.55	21.05	0.98				1261±14	3.5			
03 37 44.72	−35 19 18.8	21.71	21.15	20.91	0.98				1192±14	3.0			
03 37 46.77	−35 39 23.8	21.72	20.98	20.59	0.98				1337±9	5.7			
03 37 56.37	−35 39 15.2	22.57	22.05	21.84	0.98				1530±18	3.3			
03 39 04.55	−35 15 35.2	21.01	20.34	19.97	0.98				1506±4	12.2			
03 39 15.34	−35 35 34.7	21.14	20.55	20.23	0.41 ^e				1528±13	4.1			
03 39 24.66	−35 05 17.6	21.71	21.11	20.86	0.98				1315±10	4.8			
03 39 36.05	−35 15 13.3	22.12	21.43	21.10	0.98				1520±12	3.8			
03 39 40.13	−35 18 35.7	21.44	20.78	20.51	0.98				1402±9	6.4			
03 39 45.82	−35 17 46.3	21.84	21.12	20.74	0.97				1356±8	5.7			
03 39 49.16	−35 34 46.3	21.32	20.81	20.54	0.97				1792±11	4.1	NGC 1427A	1.6	
03 39 53.63	−35 01 33.0	21.38	20.78	20.55	0.98				1409±11	5.4			
03 40 00.71	−35 41 58.6	21.71	21.02	20.65	0.97				1452±10	4.9	NGC 1427A	4.0	
03 40 02.52	−35 36 48.8	21.65	21.01	20.64	0.98				1734±13	3.4			
03 40 02.79	−35 38 57.3	21.32	21.61	20.32	0.97				1472±9	4.9	NGC 1427A	3.8	
03 40 06.75	−35 29 27.4	21.51	20.86	20.53	0.97				1258±9	4.6			
03 40 23.31	−35 38 32.1	21.76	21.21	20.92	0.98				1283±14	3.2	NGC 1427A	5.2	

a. These CSS are considered to be gravitationally bound to a prominent cluster galaxy other than NGC 1399 - see analysis in the text.

b. FCOS catalogue identifiers (as sequenced in the table): 1-017, 2-0231, 2-078, 4-2028, 2-073, 0-2025, 3-2027, 1-2053, 1-060, 3-2004, 1-2083 and 3-2019.

c. Photometry of these CSS has been affected by partial blending with adjacent stars.

d. UCD3 is known to have an extended stellar halo (De Propris et al. 2005), and may be eventually classified as a dE,N galaxy.

e. Photometry of this CSS has been affected by blending with a background galaxy.